HORIZON

Molecules with Sunglasses

Transcript of the programme transmitted
20th January 1992

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Dear **Horizon** viewer

Just occasionally you look for a story in an area of pure, hard science, because you feel it's about time we made a programme in that area. So it was in the case of materials science and molecular chemistry. But what I found was one of the best stories of a scientific race and discovery that I've ever come across.

This is not a film to instruct you in chemistry or molecular physics. It's a film about the excitement, the disappointment, the satisfaction and sheer chance of doing science; about winning and losing; about what it is that drives researchers to ask basic questions, only to get the most surprising of answers.

Before I started making this film, I never thought a molecule could be so much fun.

John Lynch
Producer

NARRATOR (JULIET STEVENSON):

Carbon: its atoms are in every cell of our bodies. It's the heart of all that sustains life on Earth. By chance, what science could not believe existed has been found – a new form of pure carbon.

PROF. RICK SMALLEY (*Rice University, Houston*):

For 10,000 odd years we've only had diamond and graphite.

PROF. HARRY KROTO (*University of Sussex*):

Now, at the end of the 20th century, we've discovered a third form of carbon.

PROF. DON HUFFMAN (*University of Arizona*):

Something that probably no one had ever before seen in the history of mankind.

DR LOWELL LAMB (*University of Arizona*):

I was there, I can say that I was there.

PROF. RICK SMALLEY:

Chemistry has by and large been the subject of studying carbon. How could we have missed something like this?

NARRATOR:

A new form of carbon – a new chemistry; new materials; new engineering at a molecular scale.

This story of discovery and revolution in chemistry begins with astronomy: the death of stars and the birth of planets. Dying stars are pumping out carbon atoms into the interstellar medium.

PROF. HARRY KROTO:

The carbon in our body originated in space. Indeed we now know that it was ejected from some star a long, long time ago, and then

reprocessed and it ended up in the Earth's biosphere. What is absolutely fascinating, and certainly something that excited me when I first discovered it, is that every one of us is made of carbon and, therefore, every one of us is made of stardust.

NARRATOR:

Ten years ago, Harry Kroto was studying stardust.

PROF. HARRY KROTO:

One thing we're not so sure about is: what is the form of that dust, what is the structure, how does the carbon nucleate to form these little wodges that go on to grow into planets?

NARRATOR:

Diamond and graphite are the earthly forms of pure carbon. Its atoms can exist only as molecules. In living tissue they mix with hydrogen, nitrogen or oxygen to form organic molecules that build creatures and trees; and decay to soil, coal and oil. But in space, atoms can exist alone or in chains and clusters.

PROF. HARRY KROTO:

We were working on some longish chain carbon molecules and I wanted to do experiments in the laboratory to see whether we could simulate carbon star atmospheres and the chemistry in these objects – to find out if we could in fact see these long chain molecules in the laboratory.

NARRATOR:

The story also begins with light. All molecules absorb light energy as it strikes them. Each molecule's absorption is unique, and shows as a pattern of dark bands in the spectrum: a fingerprint. Be it in radio, microwave, the visible, or infra-red, on Earth or in space, somewhere in the spectrum everything has a signature. So the contents of interstellar dust can be deduced from its absorption bands. And there is one signature that has been seen but never identified: the Diffuse Interstellar Bands.

Kitt Peak Observatory was a pioneer in the discovery of molecules in space. In nearby Tucson, even the physicists were interested in astronomy.

PROF. DON HUFFMAN:

The thing that got me most interested about astronomy was this amazing mystery of the Diffuse Interstellar Bands. None of these have yet been explained by anything on Earth and so when I was a young assistant professor at the University of Arizona and I began talking with the astronomers, I began to realise that perhaps there was something out there that we hadn't made on Earth and perhaps the discovery of that would be a really exciting challenge to pursue. So when I learned of this I immediately, in my young wisdom, thought I knew the answer – and even published a paper on it, which was of course wrong.

NARRATOR:

In 1982, Huffman took a sabbatical in the Black Forest in Germany, at the physics lab of Wolfgang Krätschmer in Heidelberg. They wanted to study the ultraviolet spectrum of tiny particles of carbon dust.

PROF. WOLFGANG KRÄTSCHMER (*Max-Planck Institute*):

This is the – so to speak – historic machinery where Don Huffman and I made the first dust experiments.

NARRATOR:

It worked like an arc-welder, pushing an electric current through a couple of sticks of graphite, carbon, but inside a bell-jar, in a vacuum. It made a cloud of vaporised graphite: carbon dust. They collected the dust and, shining an ultraviolet light through it, produced an ultraviolet absorption spectrum. And it was not at all what they expected. Instead of a smooth curve, at a wavelength of about 220 nanometres they got a line with a double hump – a sort of double absorption band.

PROF. DON HUFFMAN:

Krätschmer dubbed this *Kamel* spectrum and thereafter we called it

the 'camel' spectrum, and that set off a discussion, a long-term discussion between Krätschmer and me. I suggested originally that maybe we had a new solid form of carbon.

PROF. WOLFGANG KRÄTSCHMER:

He was believing it must be something very, very peculiar. And I was believing it was just junk.

PROF. DON HUFFMAN:

And then I would suggest that, well, maybe we had long chain molecules of carbon such as were being discussed in those days.

PROF. WOLFGANG KRÄTSCHMER:

And I was arguing it was just junk.

PROF. DON HUFFMAN:

Then I think Krätschmer came up with some suggestions of his own.

PROF. WOLFGANG KRÄTSCHMER:

And so we were arguing that this may be some kind of combined structure which is new.

PROF. DON HUFFMAN:

And of course my response was: Ah, it's probably just junk. So junk was our favourite explanation for the spectrum for quite a few years.

NARRATOR:

Three years later, Harry Kroto would have given a Nobel Prize to get his hands on that junk.

The third leg of the story took place in Houston, Texas. In 1984, Kroto visited his friend Bob Curl at Rice University – which had the best system in the world for looking at clusters of vaporised atoms – in the hope of making new materials to make catalysts, or semiconductors.

PROF. RICK SMALLEY:

Most materials, like this silicon for example, need to go to many thousands of degrees to be vaporised. Well, there's an easy way of doing that with these modern lasers. Here's a silicon disc – and bring the laser in and as we come into the focus here we're generating a little plume of silicon atoms well over 10,000 degrees, easily hotter than the surface of any star. But what good is it if it's just here in the air, forming silicon oxide? What we really want to do is to collect these silicon atoms as they're knocked off and aggregate them together in a little cluster into this big machine down here that we built to study those clusters. Ultimately it comes on into this large chamber and on the inside of this at the back it strikes the target material that we're trying to vaporise to produce clusters.

NARRATOR:

The clusters rush back, get ionised by another laser, and pushed up by an electric field to a mass spectrometer. It counts how many clusters there are, and how many atoms in each.

PROF. RICK SMALLEY:

Overall it's a very simple apparatus, although it looks rather forbidding.

NARRATOR:

Smalley was working on clusters of silicon, but when Harry saw the lab he thought of carbon, and space.

PROF. RICK SMALLEY:

Hotter than the surface of any star . . .

PROF. HARRY KROTO:

When I went over to Rick's lab and saw the machine in the flesh, it was just fascinating. And almost immediately I realised that if we substituted graphite for silicon we could make a plasma similar to that in the shell of a carbon star. We could simulate that chemistry

and perhaps make the carbon chains that we had detected a few years earlier in space.

PROF. RICK SMALLEY:

We told him: That's fine, all this astrophysical stuff sounds very interesting, but it frankly wasn't really what we wanted to do in this laboratory. After all, we already knew everything there was to know about carbon, at least we assumed so. So we told Harry, Yes, fine, some other time, maybe this year, maybe next.

NARRATOR:

And Harry's experiment had already been done. The oil giant, Exxon, is interested in carbon. They had put graphite into a system like Smalley's.

DR ANDY KALDOR (*Exxon Research & Engineering*):

Carbon was a horrendous mess, made the machine absolutely filthy, but one of the interesting benefits of the experiment was that we ended up seeing a very unusual mass spectrum.

NARRATOR:

This is the mass spectrum of clusters they produced. There were small clusters with odd numbers of atoms, then a gap, then even-numbered clusters, all suggesting unusual chains of carbon. But the big ones, twice as abundant as the rest, were the clusters of 60 atoms: C_{60}. These the Exxon team reported, but made no more of.

DR ANDY KALDOR:

We did not identify C_{60} or C_{70} as being stable, or somehow unusual. But it's the name of the game. I think, you know, in retrospect, we can say that I was being cautious. At the time I was considered by most of my colleagues as being pretty wild, even daring to publish those results.

PROF. HARRY KROTO:

Almost a year and a half later, after I'd been to Houston, I got the call from Bob right out of the blue. He said that Rick had decided that we could do the experiment.

PROF. RICK SMALLEY:

One particular day I gathered my students in and said, 'What's the worst possible thing that could happen?' This is to Sean O'Brien and Jim Heath, and they said: 'Harry's coming!'

PROF. HARRY KROTO:

I was so excited I pinched some money out of my wife's bank account, got the cheapest ticket I could and was there within three days. I was keen on doing the experiment myself, and really absolutely over the moon that I could do it.

NARRATOR:

What followed none of them will forget. Harry worked with the students, doing run after run of graphite vaporised by laser. He and his friend Bob Curl bounced ideas between them. Smalley drifted in and out to see how they did. It was practical, creative science at its best. They saw evidence of Harry's long chains of carbon atoms, captured fleetingly by the laser. They also saw something else: the clusters of 60 atoms that Exxon had seen – but more of them. Again and again, 60 was the cluster that carbon preferred.

Now Rick really did get interested in what Harry was doing. Why did carbon atoms form such a stable cluster? What was special about the magic number 60?

PROF. RICK SMALLEY:

If there's any element where we know how it bonds it's carbon. That's what chemistry has largely been about for several hundred years. We know with many examples that carbon likes to bond usually with four other atoms, and in fact in diamond, the pretty form of carbon, that's exactly what it does. I have a model of a little piece of the diamond lattice here. You can see that each carbon atom,

for example this little black dot, connects through these green bonds to four other carbon atoms. That is except if they're on the surface, in which case there aren't the little black balls to connect with and these dangling bonds don't know what to do.

Now, ordinary diamond doesn't have a problem with this because hydrogen is used to terminate each and every one of these bonds. In fact, if you have a diamond ring on your finger and you move your finger across the surface of the diamond you're not touching carbon at all; in fact you're rubbing a single atomic layer of hydrogen on the surface. But we knew we didn't have any hydrogen in the machine.

There is another way that carbon can bond that we know about as chemists, and that's with just three other atoms. The most common form of this, as we know, is just plain old graphite. This is huge planes of sort of chicken-wire, lattices like this, connected six-membered rings, each carbon connected with three others, and in graphite there's one plane against another stacked up, but once again there are these edges.

NARRATOR:

These dangling bonds should make a tiny cluster attract other carbon atoms, and grow. Yet here they had a cluster that stopped at 60. Why?

PROF. HARRY KROTO:

We wondered what could possibly make it so strong. We thought about many possible structures and as it went up and down like a yo-yo on various runs that we did, we came to the conclusion that perhaps it was a closed cage of some sort.

PROF. RICK SMALLEY:

Let's suppose we go back just to a single large sheet, and this has roughly 60 carbon atoms. Obviously it has a lot of dangling bonds around the edges, but suppose somehow these are able to wrap around so that they can connect to each other. Maybe there was some way of wrapping that sheet around to do it, but we couldn't really imagine how that would be done.

PROF. HARRY KROTO:

One image which was in my mind from way back was that of Buckminster Fuller's dome at Expo '67.

NARRATOR:

The design of lightweight spherical structures was the life's work of the American architect Buckminster Fuller. His was the idea of the geodesic dome.

PROF. HARRY KROTO:

In fact at one time I'd considered writing to him for a job, because I was interested in many of his ideas, but at the same time I was offered a job at Sussex and so I finally plumped for a career in science rather than one in architecture and graphics and design. I'd been in Montreal at Expo '67, and I remembered going into Buckminster Fuller's dome and pushing my son in a pram up amongst the escalators towards the struts – the intricate structure – that held the dome together. It really did seem to be made up almost completely of hexagons.

PROF. RICK SMALLEY:

Here, after all, we had a hexagonal sheet. Maybe if we figured out how Buckminster Fuller did this we could figure out how to curl these things around on each other.

PROF. HARRY KROTO:

The other thing that I remembered, as well as Buckminster Fuller's geodesic dome, was a stardome – a map of the sky – on a polyhedron that I'd made for my sons many years beforehand. In my memory it had hexagons but it also had pentagons. I wondered whether it had 60 vertices, and thought about ringing my wife and getting her to count it, but I was going home the next day so I thought: 'Well, I'll count it myself when I get there.'

NARRATOR:

At Harry's farewell Mexican meal they talked of layers of graphite, closed cages, C_{60} and beer.

PROF. HARRY KROTO:

We were drawing on the serviettes and drinking Mexican beer and we were really very excited about what C_{60} might actually be.

NARRATOR:

Rick went home, drew out and cut up little paper hexagons. Harry went to bed thinking of the stardome, stored in a box in his basement. Sixty jelly-beans joined by cocktail sticks was the scheme adopted by graduate student Jim Heath. The jelly-beans collapsed. The hexagons would curve only by cheating. Hexagons side by side only make a flat surface. Then Rick remembered the pentagons that Harry had talked of. Hexagons round a pentagon. They automatically curved. They made a bowl-shape. Then more curves, more and more, all linking: a geodesic sphere. Sixty points, 60 carbon atoms: the shape of C_{60} formed in his hands.

PROF. RICK SMALLEY:

I almost called to get Harry out of bed to tell him about it, but it was three o'clock in the morning. I disciplined myself to go to sleep. We couldn't be the first people in the universe to have discovered this structure. They ought to know about it in the mathematics department, so I called up Bill Veetch, said: 'Bill, sorry to bother you this morning, but we have this hot new structure for a carbon molecule and it has 12 pentagons and 20 hexagons. I wonder if you could bother asking one of your students to find out what this polyhedral object is and give us a call back.' And he did call back; Bob Curl answered the phone and the Mathematics Chairman said, 'Well, I could explain this to you a number of ways Bob, but what you've got there, boys, is a soccer ball.' You can imagine this excitement that you've discovered a way of putting 60 carbon atoms together and it turns out not only to be beautifully symmetric, but it's a soccer ball too.

NARRATOR:

Their paper to *Nature* was a front-cover story.

PROF. HARRY KROTO:

The cover was a really beautiful picture of C_{60}. It almost looks like you're looking at stars in the sky. It was just such a fantastic moment that as I took the plane back I was on such a high that I think the aeroplane would have actually flown without the engines running.

NARRATOR:

They named their structure 'buckminsterfullerene or 'buckyballs': perfect symmetry in a molecule; a hollow cage of carbon. What properties it might bring! Symmetry enchanted the Ancients. The Greeks believed that perfect solids caged the fundamental elements: fire, earth, air, and water – the icosahedron. Slice off the points and the shape is C_{60}: a ball of carbon, a billionth of a metre wide.

Nature loves the geodesic sphere. It's seen in viruses and microscopic sea creatures. Harry and Rick had hit on a mathematical law that any number of hexagons will curve to a sphere if linked by just 12 pentagons. The Expo dome had pentagons. A tortoise needs one to curve its shell. So did Harry's stardome.

PROF. HARRY KROTO:

It was so beautiful that it just had to be right, but there were people that needed convincing – quite a lot – and the question was: how could we set about proving that it had this structure? That was really the next part of the story and to me it was something like five long years in the desert.

NARRATOR:

A cluster you cannot see or touch: how do you prove the shape of something measured in electric fields, held for only milliseconds in a laser beam; in existence only as long as the experiment? A cluster of 60 atoms was all they were certain of. The sphere, the soccer ball: all that was theory.

The theory ran into trouble from those who had handled carbon-60 before. The Exxon team argued that maybe there were no more C_{60} clusters than other sizes; only that conditions in the laser might make them show up more. C_{60} might not be 'special' at all.

In Houston, they tried to prove the structure by breaking the cluster apart and measuring the pieces.

PROF. RICK SMALLEY:

This is Texas and we have big lasers and we have knobs we can turn up and we can make the laser tremendously powerful, enough to drill through a hunk of metal. We found that we could finally turn it up so that C_{60} would fragment. The amazing thing is that it fragmented by losing little C_2 pieces, dimers of carbon. You've got a ball, you blast it with laser, get it very hot, it evaporates C_2 off the surface and shrinks, and as you keep blasting laser energy it shrinks more and more and more.

NARRATOR:

They got readings of C_{58}, C_{56}, C_{54}, and on down till the strain on the atoms was too great.

PROF. RICK SMALLEY:

It's just what you would expect if in fact it really were these closed cages: when you blast it there aren't any edges, no places can just fall right off, so it shrinks down until finally, critically, at C_{32}, it bursts. For most molecules that would already have been considered a proof of the structure, but this is too important a molecule to just casually say you've proved it.

NARRATOR:

Exxon kept up the counterpoint. They said the whole thing could be just an experimental artefact.

In Sussex, Harry's team could rise to theoretical models. He worked out possible structures of other carbon clusters that had appeared in the laser. A hypothetical family of 'fullerenes' was born.

PROF. HARRY KROTO:

One thing that was clear was that all the pentagons were isolated and all the hexagons were linked. That seemed to be a critical factor in the stability, and I started to wonder at what stage that would occur again. I knew it couldn't happen for anything less than 60 atoms. And as I went on higher and higher I realised that I couldn't do it again until we got to the number 70. We'd already got a structure for 70 in which we take the two halves apart and we put an extra ten carbon atoms around the waist. And then I realised that this explained the second peak. Now we had found that the C_{60} signal always had a companion – C_{70} – and I used to call the two together the Lone Ranger and Tonto. At the point when you have a hypothesis which explains two major results, then you can be sure it's right. And at that point I realised that I would not have to commit suicide over the buckminsterfullerene idea.

NARRATOR:

So Harry persuaded the British Research Councils that C_{60} research was worth funding. He bought a cluster beam. The goal was to make C_{60}, to be the first to hold it in his hands.

PROF. HARRY KROTO:

Apart from proving it, there was another major impetus and that was the fact that I still felt that C_{60} had some tie-up with the Diffuse Interstellar Bands, and if that could be proven it would solve one of the longest-lasting problems in astronomy.

NARRATOR:

The stability of C_{60} in intense laser light meant it might well survive if formed in space.

PROF. RICK SMALLEY:

In fact it turns out that C_{60} is extraordinarily photoresistant, it is the most photoresistant molecule we've seen, which will be very important if C_{60} is to be found in space, because in space molecules don't have sunglasses. You've got all these stars out there, what's to protect this molecule from getting sunburnt over the hundreds of

millions of years it's wandering out in space?

NARRATOR:

But to get a fingerprint for C_{60}, to see its absorption bands, on Earth or in space, they had to make enough of it to measure: to shine light through. They hoped that somewhere in the lasers, C_{60} had remained intact. But it was never to be found in the laser soot.

PROF. RICK SMALLEY:

So, for years actually, squandering the life of my major graduate student, Jim Heath, we scraped soots off, put them in test-tubes, sloshed them around and looked – and for years all we saw was soot, sort of floating around, or sitting at the bottom. Well, it's a lot of fun to do for a while, but for a year and a half it gets to be kind of boring. So we pretty well gave up.

NARRATOR:

But soon, paper after paper appeared from theoreticians. They were having a field-day predicting the properties of such a molecule. The perfect symmetry of C_{60} made it possible to calculate how a 'buckyball' would rotate and vibrate. The movements of the molecule and its electrons are what causes light to be absorbed by it. So absorption bands for C_{60} were calculated. Its fingerprint in the spectrum, at least in theory, was available in print. And in Tucson, Don Huffman had read it.

PROF. DON HUFFMAN:

When I saw the Kroto/Smalley paper in *Nature* I was very excited because I immediately began to think that perhaps the 'camel' sample wasn't junk after all. One of the calculations had to do with the ultraviolet spectrum to be expected of a C_{60} molecule. It had a series of very strong bands in the ultraviolet, and if one put that on the same scale as our camel spectrum, there was a nice, interesting correspondence there, and this kept us wondering for a long time. Unfortunately that was about the time when I was very busy with other things and I went to the laboratory and had trouble reproducing the 'camel' spectrum.

NARRATOR:

So he set a graduate student with a bell-jar to make soot that would reproduce the camel.

DR LOWELL LAMB:

This was my first job in the lab, so since not very many people expected it would work out, there wasn't really very much pressure on me to produce results. It's really a very simple experiment – which is a good thing, because it was such a long shot. It's a simple, simple device. There's a carbon arc discharge in a vacuum chamber with a little helium in there. There aren't many things you can change. We changed the tip size, we changed the voltage in the current, but it turned out that the most important thing was the pressure setting. When you have the pressure at about 100 torrs, which is about a seventh of an atmosphere, those two funny bumps come back: the 'camel' spectrum, the thing that we had seen in Heidelberg.

NARRATOR:

In Heidelberg, Krätschmer put their sooty specimens into an infrared spectrometer. He looked for absorption in a different part of the spectrum – infra-red. He saw four absorption bands. And in theory, that too was predicted for C_{60}.

PROF. WOLFGANG KRÄTSCHMER:

The main result was that those samples which also showed this peculiar ultraviolet feature which we called 'camel' hump also show four infra-red bands at almost exactly the same positions as predicted by theory for C_{60}. And we published this, and we could show at least that the four infra-red features are definitely produced by carbon alone and they are not any kind of junk.

DR LOWELL LAMB:

At the same time we were very alarmed because in publishing the letter on the dust we had essentially given away the secret, and if *we* could figure out how to extract C_{60} from the soot, then any real

chemist certainly could, and probably they were following right behind us.

NARRATOR:

His fears were justified. Krätschmer presented their results at an astronomy conference in Capri, and the paper found its way to Harry Kroto.

PROF. HARRY KROTO:

I received this paper which Mike Jura sent to me, and he wrote on the top: 'Harry, presented at Capri – do you believe this?' When I read it, it was such a simple way of making C_{60} I just couldn't believe it.

NARRATOR:

Believe it or not, he dispatched two students to evaporate carbon.

JONATHAN HARE (*University of Sussex*):

It was pretty ropy old equipment. When me and Amit first worked on it, it worked for about three or four days and then all the electronics just burnt out. So I had to rebuild all the equipment. One of the things that we could do was the mass spectrum, and downstairs this was run by Ali Abdul Sadah. The sample was run while I was away in Scotland on holiday, and we got this fantastic result. Ali came down clutching this bit of paper, saying, 'We have fantastic news. Do you want the good or the bad news?' And the good news was that they got this peak where they expected to see C_{60}, and the bad news was that the machine broke down so we couldn't repeat it.

NARRATOR:

At least they'd made C_{60}. But how could they extract it from the soot?

JONATHAN HARE:

We'd been collecting it for several months. So one Friday, one brave Friday, I had, I suppose, perhaps half a test-tube of soot, and I thought I'd better do something. And one idea was just simply using

a solvent to try and dissolve C_{60} out. So I got half of the soot I produced and I basically just got some benzene, put it in the tube and shook it up with the soot. Just shook it up and put it on the top of the shelf and left it there over the weekend. When I came in on Monday morning there was this red solution. I went round the laboratory going, 'Look, C_{60}'s in here.' And everyone was sort of going, 'Yeah, OK Jon.' But it turned out in the end, in fact, that's exactly what it was.

NARRATOR:

For five days Harry thought they had the first solution of C_{60}. And then . . .

PROF. HARRY KROTO:

Well, I had a call from *Nature*, the journal, and they said, would I referee this paper? So I said, fair enough. I knew a fair amount about this topic and they faxed me a copy of their paper and it was a bombshell. There they had beautiful crystals. They had infra-red. They had an X-ray structure. They had made the molecule beyond all doubt and we had been pipped at the post.

NARRATOR:

It was of course Huffman and Krätschmer's paper.

PROF. DON HUFFMAN:

The amazing thing is that the whole process was so incredibly simple. Once we'd found that the carbon-60 was soluble as a red liquid, all we had to do was dry it out and that left us with the solid that we were so eagerly seeking. The easy way to do that is just pour it on the hotplate and let it dry for a few minutes, and there's the solid that we wanted to do the experiments with.

Now the way it really happened was Krätschmer called me from Germany and said, 'If you just take a little vial of the red material and you put a drop of it on a microscope slide then you will see an incredibly beautiful sight.' So I reproduced the experiment by putting a tiny drop of the red liquid on the microscope slide. And in

just a very few seconds I was able to see these beautiful little crystals which were hexagonal platelets of a brownish-orange colour.

NARRATOR:

No longer fleeting atoms in a laser; not merely in red solution – now a new solid. Pure carbon crystals.

PROF. DON HUFFMAN:

We realised by this time that we were surely seeing a crystalline form of carbon-60, which was really a genuinely new form of carbon, and that we were probably the first people on Earth ever to see this sight. And as a solid-state physicist it was incredibly nice to be able to say, Aha, now we've got something that we can really begin to experiment with, we can see it and work with it. And that was really the moment of high excitement for me.

PROF. RICK SMALLEY:

And here, suddenly, from a stunningly simple technique, by physicists my God, not chemists, were the first macroscopic isolated amounts of carbon. Of course we'd been scooped, but it was so wonderful.

PROF. DON HUFFMAN:

Looking back at it now after I've talked to Harry and Rick and gotten to know them pretty well, I can't help but feel a little bit sorry for them because they were trying so hard to see the yellow stuff and we sort of had it in our hands all the time.

PROF. RICK SMALLEY:

We'd in a sense tried too hard with high technology and not just simply gone down and tried the simplest thing – just evaporate carbon, collect the soot and see what happens. But no matter. I mean, if we'd done it early on, then Huffman and Krätschmer couldn't have had so much fun.

NARRATOR:

In 1990 there was a surge in sales of arc-welders, as chemists the world over set out to make C_{60}. Every arc and every bell-jar is different – all with an eye to the patent lawyer.

PROF. RICK SMALLEY:

Our apparatus should be in the *Guinness Book of Records* for the largest number of arc welding power supplies ever connected in parallel at any time. We need that many power supplies because we're vaporising big sticks of graphite here, half-inch diameter. We feed one in from either side with some screw mechanisms and when they meet in the middle the arc that's formed is really quite ferocious. We do that because we want to vaporise and make a lot of 'buckys'. When we do it in this chamber we have to get them out of there quickly, so we actually suck them out through the top here with something that's very much like a vacuum cleaner. In fact it *is* a vacuum cleaner – it's my personal home vacuum cleaner from Sears, and there's a Sears Kenmore vacuum bag here to collect the soot. We're actually one-stop shoppers at Sears.

NARRATOR:

On the campuses, C_{60} has shaken up an ancient science. Organic chemistry means carbon chemistry. And carbon-based molecules have always been flat. One chemist had prayed to escape that flat-earth view – prayed for C_{60}, five years before Kroto and Smalley even dreamed of it.

PROF. ORVILLE CHAPMAN (*University of California, Los Angeles*):

At the beginning of the eighties I felt that organic chemistry was in great disarray. It had turned inward, it was a self-absorbed science, not interested in other sciences. I sought to answer a single question: If God would give me the grace to make one molecule, what would that molecule be? Ultimately I decided it would be a carbon sphere, and I chose C_{60}. The scientific community reacted with laughter.

NARRATOR:

The sweatshirts he printed ten years ago are now collectors' items. Today, his former students are very excited about the new 3-D world.

PROF. FRANCOIS DIEDERICH (*University of California, Los Angeles*):

Now we have spherical molecules, we have benzene rings that are assembled in three dimensions on the sphere, and the rules of the chemistry of buckminsterfullerene are entirely different from those that we normally use. So we have to invent new chemistry.

NARRATOR:

The aim is to attach other chemicals. Then more can be done with C_{60}. Chains of bucky-balls, polymers, molecular wires – all become possible. At UCLA they've looked at the bigger fullerenes, and found one that has created another ball game. It is C_{76}, and it comes in two varieties.

PROF. FRANCOIS DIEDERICH:

We see in this compound of C_{76} a helix that winds clockwise. In the other compound of C_{76} we see a helix that winds counter-clockwise. Now this is a general principle in the biological world. All biological material – sugars, DNA, peptides, proteins are either left-handed or right-handed. Out of graphite, an inorganic flat material, we have made helical material, just like biological material, and this might be very interesting and might have importance for the origin of life.

PROF. ORVILLE CHAPMAN:

It is certainly a revolution in the subject. One has now a molecular carbon to work with. The applications, all of these very intriguing things that are appearing, are only the tip of the iceberg.

NARRATOR:

Buckyballs have also electrified solid-state physics. AT&T's Bell Laboratories have grown crystals of C_{60} and put potassium atoms in the spaces of the crystal lattice. C_{60} loves to attract electrons, and

potassium loves to give them away. They found the crystal was an electrical conductor. Three weeks later, that it was a superconductor, with no resistance to electricity. That means that everyone wants to work on C_{60} .

PROF. DON HUFFMAN:

I happened to have been asked to be a referee on the conductivity paper from Bell Labs and I'll never forget the day I received that and opened it up and looked and there were eighteen authors on the paper. And I began to think, What am I doing in this field? I am a lone researcher with a colleague in Germany, competing with one of the finest groups in the world. And here I am receiving telephone calls from all over the world and not only can I not compete with Bell Labs, but I can't even hardly answer all the telephone calls I get!

NARRATOR:

At Exxon, Andy Kaldor has long got over any pain of missing a discovery. Now he's throwing researchers at it.

DR ANDY KALDOR:

One of our interests is to see what it is that you can do with C_{60} once you make it behave differently to how it does just as a pure material. And part of our research strategy is to try to find if it can impact on the larger arena, perhaps an appropriate oil additive. We'd love to be the company that finds a way of putting a fullerene into a can of oil that would improve the performance of engine oils. *Love* to be the first company to do that.

NARRATOR:

At the US Naval Research Laboratories, they've calculated the strength of the atomic bonds of a buckyball. Fired, in a computer, at a theoretical diamond surface, with enough calculated energy to split any other molecule asunder, C_{60} would simply bounce. The geodesic properties that made Buckminster Fuller's domes so strong also apply at the molecular scale.

DR ANDY KALDOR:

You have this rather beautiful structure, in many different forms but they're all pretty nice, and one could imagine trying to find ways of linking these materials together. There's a lot of interest in trying to build essentially buckyball structures. What those materials will turn out once you've successfully built them I cannot predict.

PROF. RICK SMALLEY:

We could coalesce, for example, just two C_{60} balls together, and it would look something like an object which currently is called a 'coalesced bucky-tube'. It's a hollow graphitic tube and you could imagine it getting infinitely long, to be a fibre for that matter, or short, or various lengths. Think of these tubes as being pipes in a nanometre architecture, in construction projects to build houses, factories, that all exist on a nanometre scale; or we can make who knows what – catalytic reaction centres, photosynthetic centres, semiconducting devices. A whole range of technology may be waiting for us on the nanometre scale.

DR ANDY KALDOR:

There's a big difference between scientific excitement, which I think is fantastic, and the ability to deliver a product for somebody to use. The fastest development of a completely new concept usually is in the order of a couple of years, maybe three years. We are still in the first year. Give us a chance. I think that, for very specialised high-value-added products, we will begin to see some applications at the end of '92 or early '93.

PROF. HARRY KROTO:

We've spent five years now working with this molecule, and to some extent the science of C_{60} has changed. It's become technology in some areas. People have it in their hands. It's no longer a figment of one's imagination. We're going to do some work in this area. We're going to probe its organic properties. We're going to probe some applications in soot chemistry. But part of my work will go in a different direction.

PROF. DON HUFFMAN:

Everyone seems to be jumping on the bandwagon of doing carbon-60 research, and this is something that happens in science, but frankly it worries me a little bit as to my involvement because I tend to like to be off by myself. That's one reason I like to live in Arizona – because I don't like crowds very much.

PROF. HARRY KROTO:

Really I like working in the dark. For me science is something to do with fun and solving puzzles where I really don't know what the answer is. To some extent I know too much about C_{60} now.

PROF. DON HUFFMAN:

I have a difficult decision to make as to whether to continue in the many interesting things that there still are to do in fullerene research, or whether it's time to go chase some more obscure puzzles that still are out there to be solved.

PROF. WOLFGANG KRÄTSCHMER:

There is a kind of irony of the whole story – that, even though we found C_{60} and we were keen to observe it or to say that this may also be abundant in interstellar space, in my view at least it looks like it is not very abundant at all in interstellar space.

PROF. DON HUFFMAN:

If that's so, of course, in a sense we've all been failures in this. But what a wonderful failure it's been.

PROF. WOLFGANG KRÄTSCHMER:

I take it not really as a disappointment.

PROF. HARRY KROTO:

I believe it is there, and it would be rather nice to feel that we were on the right track. There are some interesting features in space and C_{60} certainly can fit them better than any other proposal that has

been made up to now. I'm a believer, and I think ultimately we'll find that it is there.

INTERVIEWER:

But others have said that C_{60} is nothing like a match for the Diffuse Interstellar Bands.

PROF. HARRY KROTO:

They're wrong.

Produced and designed by Broadcasting Support Services for **BBC Horizon.**

Printed by In Speed, Luton

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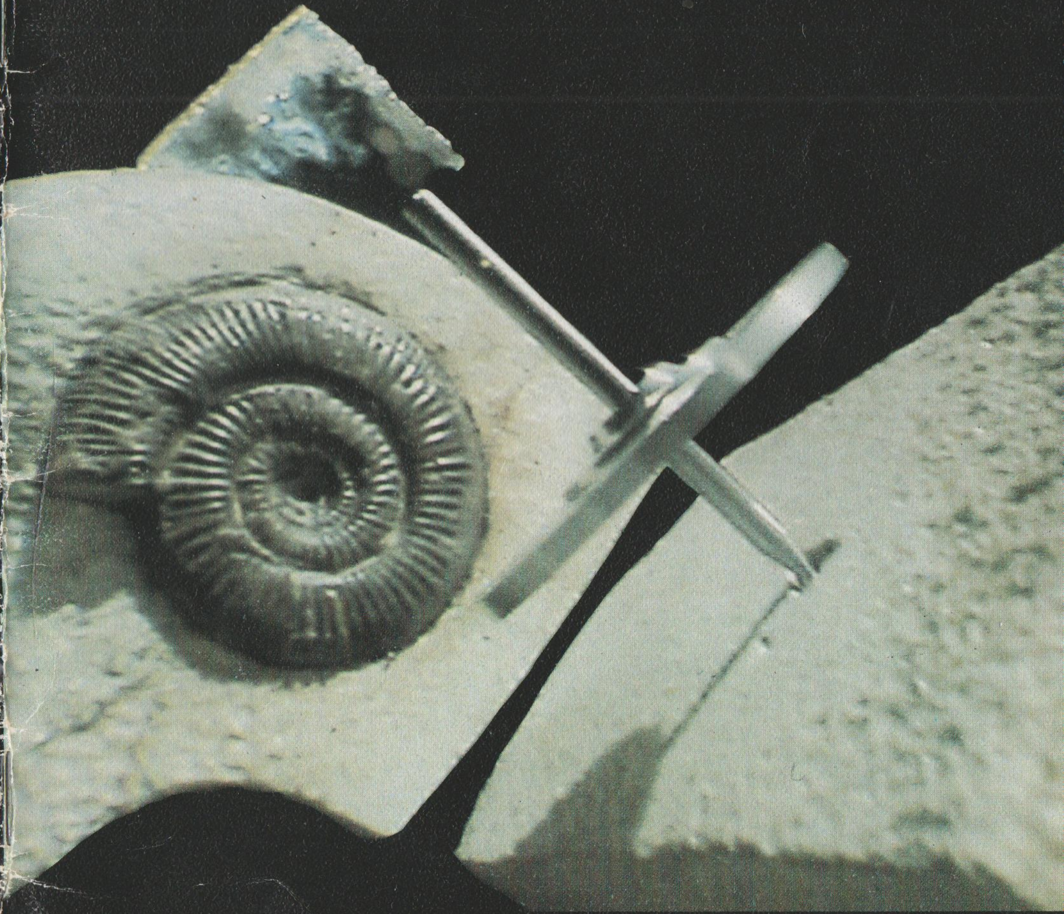

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Transcript of the programme transmitted
20th January 1992